Choked flow

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Choked flow is a compressible flow effect. The parameter that becomes "choked" or "limited" is the velocity or the mass flow rate.

Choked flow is a fluid dynamic condition associated with the Venturi effect. When a flowing fluid at a given pressure and temperature passes through a restriction (such as the throat of a convergent-divergent nozzle or a valve in a pipe) into a lower pressure environment the fluid velocity increases. At initially subsonic upstream conditions, the conservation of mass principle requires the fluid velocity to increase as it flows through the smaller cross-sectional area of the restriction. At the same time, the Venturi effect causes the static pressure, and therefore the density, to decrease downstream past the restriction. **Choked flow** is a limiting condition which occurs when the mass flow rate will not increase with a further decrease in the downstream pressure environment while upstream pressure is fixed.

For homogeneous fluids, the physical point at which the choking occurs for adiabatic conditions is when the exit plane velocity is at sonic conditions or at a Mach number of 1.[1][2][3] At choked flow the mass flow rate can be increased by increasing the upstream pressure, or by decreasing the upstream temperature.

The choked flow of gases is useful in many engineering applications because the mass flow rate is independent of the downstream pressure, depending only on the temperature and pressure on the upstream side of the restriction. Under choked conditions, valves and calibrated orifice plates can be used to produce a desired mass flow rate.

Contents

- 1 Choked flow in liquids
- 2 Mass flow rate of a gas at choked conditions
  - 2.1 Choking in change of cross section flow
- 3 Thin-plate orifices
- 4 Minimum pressure ratio required for choked flow to occur
  - 4.1 Vacuum Conditions
- 5 See also
- 6 References
- 7 External links

Choked flow in liquids

If the fluid is a liquid, a different type of limiting condition (also known as choked flow) occurs when the Venturi effect acting on the liquid flow through the restriction decreases the liquid pressure to below that of the liquid vapor pressure at the prevailing liquid temperature. At that point, the liquid will partially flash into bubbles of vapor and the subsequent collapse of the bubbles causes cavitation. Cavitation is quite noisy and can be sufficiently violent to physically damage valves, pipes and associated equipment. In effect, the vapor bubble formation in the restriction limits the flow from increasing any further.[4][5]

Mass flow rate of a gas at choked conditions

All gases flow from upstream higher pressure sources to downstream lower pressure sources. There are several situations in which choked flow occurs, such as the change of cross section in a de Laval nozzle or flow through an orifice plate.

Choking in change of cross section flow

Assuming ideal gas behavior, steady state choked flow occurs when the ratio of the absolute upstream pressure to the absolute downstream pressure is equal to or greater than $\mathbf{[(k + 1) / 2]^{k / (k - 1)}}$, where **k** is the specific heat ratio of the gas (sometimes called the isentropic expansion factor and sometimes denoted as γ).

For most gases, **k** ranges from 1.09 (e.g. butane) to 1.67 (monatomic gases), and therefore $\mathbf{[(k + 1) / 2]^{k / (k - 1)}}$ ranges from 1.7 to about 2.1 ... which means that choked flow usually occurs when the absolute source vessel pressure is at least 1.7 to 2.1 times as high as the absolute downstream pressure.

When the gas velocity is choked, the equation for the mass flow rate in SI metric units is: [1][2][3][6]

$$\dot{m} = C\ A \sqrt{k\ \rho\ P \left(\frac{2}{k+1}\right)^{(k+1)/(k-1)}}$$

where the quantities are defined in the table below. If the density ρ is not known directly, then it is useful to eliminate it using the Ideal gas law corrected for the real gas compressibility:

$$\dot{m} = C\ A\ P \sqrt{\left(\frac{k\ M}{Z\ R\ T}\right)\left(\frac{2}{k+1}\right)^{(k+1)/(k-1)}}$$

so that the mass flow rate is primarily dependent on the cross-sectional area ***A*** of the hole and the upstream pressure ***P***, and only weakly dependent on the temperature ***T***. The rate does not depend on the downstream pressure at all. All other terms are constants that depend only on the composition of the material in the flow. Although the gas velocity reaches a maximum and becomes choked, the mass flow rate is not choked. The mass flow rate can still be increased if the upstream pressure is increased.

where:

- $\dot{m}$ = mass flow rate, kg/s
- ***C*** = discharge coefficient, dimensionless
- ***A*** = discharge hole cross-sectional area, m^2
- ***k*** = c_p/c_v of the gas
- $\boldsymbol{c_p}$ = specific heat of the gas at constant pressure
- $\boldsymbol{c_v}$ = specific heat of the gas at constant volume
- $\boldsymbol{\rho}$ = real gas density at P and T, kg/m^3
- ***P*** = absolute upstream pressure of the gas, Pa

M = the gas molecular mass, kg/kmole (also known as the molecular weight)

R = Universal gas law constant = 8314.5 (N·m) / (kmole·K)

T = absolute upstream temperature of the gas, K

Z = the gas compressibility factor at P and T, dimensionless

The above equations calculate the steady state mass flow rate for the pressure and temperature existing in the upstream pressure source.

If the gas is being released from a closed high-pressure vessel, the above steady state equations may be used to approximate the **initial** mass flow rate. Subsequently, the mass flow rate will decrease during the discharge as the source vessel empties and the pressure in the vessel decreases. Calculating the flow rate versus time since the initiation of the discharge is much more complicated, but more accurate. Two equivalent methods for performing such calculations are explained and compared online.[7]

The technical literature can be very confusing because many authors fail to explain whether they are using the universal gas law constant R which applies to any ideal gas or whether they are using the gas law constant R_s which only applies to a specific individual gas. The relationship between the two constants is $R_s = R / M$.

Notes:

- For any ideal gas, ***Z*** = 1
- kmole = 1000 moles

Thin-plate orifices

The flow of real gases through thin-plate orifices never becomes fully choked. The mass flow rate through the orifice continues to increase as the downstream pressure is lowered to a perfect vacuum, though the mass flow rate increases slowly as the downstream pressure is reduced below the critical pressure.[8] Cunningham (1951) first drew attention to the fact that choked flow will not occur across a standard, thin, square-edged orifice.[9][10][11]

Minimum pressure ratio required for choked flow to occur

The minimum pressure ratios required for choked conditions to occur (when some typical industrial gases are flowing) are presented in Table 1. The ratios were obtained using the criteria that choked flow occurs when the ratio of the absolute upstream pressure to the absolute downstream pressure is equal to or greater than $\mathbf{[(k + 1) / 2]^{k/(k-1)}}$, where k is the specific heat ratio of the gas. The minimum pressure ratio may be understood as the ratio between the upstream pressure and the pressure at the nozzle throat when the gas is traveling at Mach 1; if the upstream pressure is too low compared to the downstream pressure, sonic flow cannot occur at the throat.

Table 1

Gas	$k = c_p/c_v$	Minimum P_u/P_d required for choked flow
Helium	1.660	2.049
Hydrogen	1.410	1.899
Methane	1.307	1.837
Propane	1.131	1.729
Butane	1.096	1.708
Ammonia	1.310	1.838
Chlorine	1.355	1.866
Sulfur dioxide	1.290	1.826
Carbon monoxide	1.404	1.895

Notes:

- P_u = absolute upstream gas pressure
- P_d = absolute downstream gas pressure
- k values obtained from:
  1. Perry, Robert H. and Green, Don W. (1984). *Perry's Chemical Engineers' Handbook, Table 2-166,* (6th Edition ed.). McGraw-Hill Company. ISBN 0-07-049479-7.
  2. Phillips Petroleum Company (1962). *Reference Data For Hydrocarbons And Petro-Sulfur Compounds* (Second Printing ed.). Phillips Petroleum Company.

Inspection of these values leads to the inference that minimum pressure ratio is the following linear function of specific heat ratio: P_ratio = 0.6057 * k + 1.045.

Vacuum Conditions

In the case of upstream air pressure at ambient atmospheric pressure and vacuum conditions down stream of an orifice, both the air velocity and the mass flow rate becomes choked or limited when sonic velocity is reached through the orifice.

See also

- Accidental release source terms includes mass flow rate equations for non-choked gas flows as well.
- Orifice plate includes derivation of non-choked gas flow equation.
- Laval nozzles are Venturi tubes that produce supersonic gas velocities as the tube and the gas are first constricted and then the tube and gas are expanded beyond the choke plane.
- Rocket engine nozzles discusses how to calculate the exit velocity from nozzles used in rocket engines.
- Hydraulic jump.

References

1. ^ [a] [b] *Perry's Chemical Engineers' Handbook*, Sixth Edition, McGraw-Hill Co., 1984.
2. ^ [a] [b] *Handbook of Chemical Hazard Analysis Procedures,* Appendix B, Federal Emergency Management Agency, U.S. Dept. of Transportation, and U.S. Environmental Protection Agency, 1989. Handbook of

Chemical Hazard Analysis, Appendix B (http://nepis.epa.gov/Exe/ZyNET.exe/10003MK5.TXT?ZyActionD=ZyDocument&Client=EPA&Index=1986+Thru+1990&Docs=&Query=&Time=&EndTime=5E%22OSWERHCHAP%22&QFieldYear=&QFieldMonth=&QFieldDay=&UseQField=pubnumber&IntQFieldOp=1&ExtQFieldC3A%5Czyfiles%5CIndex%20Data%5C86thru90%5CTXT%5C00000003%5C10003MK5.TXT&User=ANONYMOUS&Password=anonymous&SortMethod=h%7C-&MaximumDocuments=10&FuzzyDegree=0&ImageQuality=r75g8/r75g8/x150y150g16/i425&Display=7Cf&DefSeekPage=x&SearchBack=ZyActionL&Back=ZyActionS&BackDesc=Results%20page&MaximumPages=1&ZyEntry=1&SeekPage=x) Click on PDF icon, wait and then scroll down to page 391 of 520 PDF pages.

3. ^ $^{a\ b}$ *Methods For The Calculation Of Physical Effects Due To Releases Of Hazardous Substances (Liquids and Gases)*, PGS2 CPR 14E, Chapter 2, The Netherlands Organization Of Applied Scientific Research, The Hague, 2005. PGS2 CPR 14E (http://vrom.nl/pagina.html?id=20725)
4. ^ Valve Sizing Calculations (http://www.fisherregulators.com/technical/sizingcalculations/) Scroll to discussion of liquid flashing and cavitation.
5. ^ Control Valve Handbook (http://www.chemicalprocessing.com/Media/MediaManager/control_valves.pdf) Search document for "Choked".
6. ^ *Risk Management Program Guidance For Offsite Consequence Analysis*, U.S. EPA publication EPA-550-B-99-009, April 1999. Guidance for Offsite Consequence Analysis (http://www.epa.gov/emergencies/docs/chem/oca-all.pdf)
7. ^ Calculating Accidental Release Rates From Pressurized Gas Systems (http://air-dispersion.com/feature2.html)
8. ^ Section 3 -- Choked Flow (http://www.engsoft.co.kr/download_e/steam_flow_e.htm)
9. ^ Forum post on 1 Apr 03 19:37 (http://www.eng-tips.com/viewthread.cfm?qid=51260)
10. ^ Cunningham, R.G., "Orifice Meters with Supercritical Compressible Flow" Transactions of the ASME, Vol. 73, pp. 625-638, 1951.
11. ^ Richard W. Miller (1996). *Flow Measurement Engineering Handbook* (Third Edition ed.). McGraw Hill. ISBN 0-07-042366-0.

External links

- Additional accidental release source terms (http://www.air-dispersion.com/source.html)
- Choked flow of gases (http://www.okcc.com/PDF/Choked%20Flow%20of%20Gases%20pg.48.pdf)
- Development of source emission models (http://www.qub.ac.uk/qc/webpages/whatwedo/researchgroups/environmentalmodelling/ia/doc
- Restriction orifice sizing control (http://www.enggcyclopedia.com/calculators/restriction-orifice-sizing) Perform orifice plate, restriction orifice sizing calculation for a single phase flow.

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